Absolute reference calorimeter for measuring high power laser pulses

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A calorimeter for making absolute energy measurements of high power laser pulses is described. The calorimeter, based on volume absorption in a solid, is calibrated electrically and requires no window or vacuum environment. An error analysis is included giving the systematic and random errors of the instrument for a laser measurement. Briefly, the following performance is typical of the 32-mm $\times$ 32-mm aperture calorimeter: range 0.4–15-J; random error $\pm0.2\%$ (one standard deviation); systematic error $\pm2.3\%$; and an upper operational limit of 3 J/cm^2. Most of the volume absorber documentation is applicable for 1.06 μm; however, the calorimeter should be useful from the near ir through the visible. Absorbers for use with CO_2 lasers in the 9–11-μm range are also discussed.

I. Introduction

Many types of instruments are available to measure the energy of laser pulses. A description of the various techniques can be found in review articles.[1,2] Certain instruments are more useful than others because of advantages in cost, simplicity, dynamic range, accuracy, precision, etc. In many instances, the instruments are not absolute and must be calibrated against references to give measurements traceable to the International System of Units. In previous reports, the absolute measurement process was often insufficiently documented so a determination of the measurement error was impossible. The present paper describes a laser calorimeter used at the National Bureau of Standards to calibrate other instruments. It will be used as the basis of an NBS measurement assurance program (MAP) for pulsed laser energy.

II. Absorber Properties

The calorimetric measurement of high power laser pulses is difficult because of high transient temperatures produced upon absorption. Surface absorbers ablate at energy densities commonly encountered in unfocused laser beams. The limitation of surface absorbers was determined by measuring the damage thresholds of typical absorbing blacks on metal substrates. Measurements were made at both 1.06 μm and 10.6 μm using Nd and CO_2 lasers at commonly used pulse lengths.

A CO_2 TEA laser operating in the TEM$_{00}$ mode with a nominal pulse length of 0.5 μsec was used to determine

damage thresholds at 10.6 μm.[3] Damage was determined by visually inspecting the absorber for signs of ablation, which was first noticeable as a slight discoloration on the surface. The lowest energy density producing a discoloration on the absorber after 1000 pulses was defined as the damage threshold. The ablation showed a very definite threshold behavior. At an energy density $\frac{2}{3}$ of threshold, the surface could be exposed to thousands of pulses without a noticeable effect; whereas, a single pulse three times higher than threshold would produce a very noticeable ablation usually accompanied by a plume. Results were also obtained at 1.06 μm with a TEM$_{00}$ mode Nd glass laser having a pulse width of 30 nsec.[4]

The damage results, shown in Table I, indicate no particular absorber has a significant advantage in damage threshold. The black copper oxide threshold should be reduced if a comparison of absorbed energy is made since the reflectivity can be 50% or more at 10 μm.[5] Threshold differences between clear and black anodized aluminum may result from the poor contrast between damage discoloration and background for the clear anodized aluminum. Because nonuniform laser beams are often encountered, a calorimeter based on any one of the absorbers would have to include a safety factor and operate substantially below 0.2 J/cm^2 for the given pulse lengths. Table I can be extended to other pulse lengths if one assumes the damage is caused by transient heating to ablative temperatures. In this case the energy density damage threshold is directly proportional to the square root of the pulse length.[6,7]

Laser energy can be absorbed in a volume without prohibitively high temperatures. A volume absorber is described by an absorption coefficient α where the laser energy density (defined in this paper as energy per

Surface	Damage threshold 10.6 μm, 0.5-μsec pulse, J/cm^2	Damage threshold 1.06 μm, 30-nsec pulse, J/cm^2
3M Black Nextel paint	0.4–0.6	0.16–0.28
Black copper oxide	0.7–1.0	
Black anodized aluminum	0.3–0.5	
Clear anodized aluminum, i.e., no sealing or dyeing process	0.5–0.8	

unit area) E as a function of distance traveled in the absorber is given by

$$E(x) = E(o) \exp(-\alpha x). \qquad (1)$$

When absorbing a laser pulse, the maximum temperature rise occurs at the front surface; the maximum rise assuming no heat transfer during the pulse is given by

$$\Delta T(o) = \frac{\alpha E(o)}{\rho c}, \qquad (2)$$

where $\Delta T(o)$ is the front surface temperature rise, $E(o)$ the incident energy density, ρ the absorber density, and c the absorber specific heat. Equation (2) gives an upper limit on the temperature rise since heat transfer can occur during the laser pulse. A measure of the time τ required for significant heat transfer from an absorption depth of $1/\alpha$ to the rest of the bulk is given by

$$\tau = \frac{\rho c}{2\alpha^2 K}, \qquad (3)$$

where K is the thermal conductivity of the absorber.[8]

Volume absorbers in the form of gases,[9] liquids,[10] and solids[11] have been previously used in laser calorimetry. Solid volume absorbers are used in the calorimeter described in this paper. Solids have a number of advantages over gases or liquids namely, windows do not have to be used to contain the absorber, leakage is not a problem, absorption is not necessarily associated with a narrow resonance line, and thermal diffusivity can be high especially in single crystals. The major disadvantage of solids, however, is the irreversibility of laser induced damage. It is therefore important to establish the damage thresholds of solid absorbers.

Volume absorbers were evaluated for use at 1.06 μm and 10.6 μm. If absorbers are to be useful in laser calorimetry, they should not exhibit damage, bleaching, fluorescence, or change in chemical potential over the operating range of laser intensities. For 1.06 μm and the visible, Schott neutral density glasses make useful volume absorbers.[11] Schott neutral density glass types NG-1, NG-10, and NG-3 have appropriate absorption coefficients to make relatively small thickness absorbers. In order to describe adequately the experimental procedure and permit reproduction of this work, certain

commercial products are mentioned here and elsewhere; in no way does this represent an endorsement by NBS.

Damage thresholds of the neutral density glasses were determined at 1.06 μm using a Q-switched Nd-glass laser operating in the TEM$_{00}$ mode with a pulse length of 30 nsec.[4] The results are given in Table II. Damage was determined by illuminating the probable damage site with a He–Ne laser. Damage was observed as a diffraction pattern in the transmitted He–Ne beam. This technique showed that damage first occurs in the glass bulk and then propagates to the surface after approximately ten shots. As might be expected from Eq. (2), the glasses with the highest absorption coefficients had the lowest damage thresholds. Equation (2) can be used to predict the surface temperature rise since Eq. (3) indicates negligible heat transfer occurs in 30 nsec. Damage is likely to occur when the glass is heated to the softening point (typically 700°C) and cooled rapidly enough to cause local crazing. Equation (2) predicts this will happen at 28 J/cm^2, 55 J/cm^2, and 91 J/cm^2 for NG-1, NG-10, and NG-3, respectively. Agreement with Table II is close enough to suspect this mode of damage is probable. Damage in one of the neutral density glasses (NG-1) was determined by Gunn[11] at a pulse length of 200 psec, and a value of approximately 60 J/cm^2 was obtained. This verifies that damage threshold is determined by the energy density in the laser pulse over a wide range of peak powers. Equation (3) predicts an enhancement in the damage threshold of NG-1 will not occur until the pulse length is greater than 40 msec; longer times are required for the other absorbers.

The NG-10 absorber was studied to see if significant bleaching could occur. Bleaching has been observed in other color glasses, especially those used as saturable absorbers for Q-switching lasers.[12] A Q-switched Nd: YAG laser with a pulse length of 20 nsec was focused with a 1-m focal length lens onto a 1-mm thick sample of NG-10. Commercial detectors employing integrating Si photodiodes were used to monitor the incident and transmitted energy. Energy of the laser pulse was varied by using a Glan polarizing prism as an attenuator thus assuring a change in only the pulse amplitude. To find the energy density incident on the NG-10, the energy passing through a small circular aperture of known diameter was determined. The transmission measurements on the NG-10 gave an absorption coefficient of 28 cm^{-1} which varied by 3% as the beam intensity was

Table II. Damage Threshold of Volume Absorbers at 1.06 μm, 30-nsec Pulse

Schott glass material	1.06-μm absorption coefficient,[a] cm^{-1}	Damage threshold, J/cm^2
NG-1	55	43 ±6
NG-10	28	74 ±12
NG-3	17	115 ±18

[a] The absorption coefficients are taken from *Color Filter Glass*, published by Schott Optical Glass, Inc.

Table III. Damage Thresholds of Volume Absorbers at 10.6 μm, 0.5-μsec Pulse

Material	Damage threshold, J/cm²
LiF, single crystal	5–8
MgO, single crystal	8–12
MgF₂, single crystal	13–20
MgF₂, polycrystal (Irtran 1)	10–20
CaF₂, single crystal	Over 30

increased from 0.2 to 10 J/cm² (10 MW/cm² to 0.5 GW/cm²). The small observed changes in transmission could have been due to nonlinearities in the detectors instead of bleaching by the NG-10. A bleaching of 3% would be negligible in calorimetric applications since the glasses are used as absorbers rather than precision attenuators. Measurements by Gunn on NG-1 and other glasses indicate no significant change in transmission up to about 300 GW/cm².[11]

A cumulative change in the transmission of NG-10 due to laser pulses was not observed. Such a change might occur by a finite change in the chemical potential on each laser pulse. To evaluate cumulative effects, a single spot on the 1-mm thick sample of NG-10 was exposed to nine hundred 1.06-μm laser pulses at 10 J/cm² (0.5-GW/cm² peak intensity). Within a 0.6% measurement precision (one standard deviation), no change was observed in the transmission.

Volume absorbers having appropriate absorption coefficients were studied for use at 10.6 μm. Although some plastics have been used at 10.6 μm, the present study mainly considered crystalline materials which are commonly used as ir windows.[13,14] These materials have higher melting points and thermal conductivities than plastics. The damage thresholds of LiF, MgF₂, MgO, and CaF₂ were determined with the CO₂ laser previously described; the damage results are summarized in Table III.[3] These materials were exposed to at least 600 laser pulses at each level of energy density with a pulse repetition rate of 1 pps or 2 pps and a beam spot size of typically 1–2 mm. In all the single crystals the observed damage was the same: two perpendicular cracks about 2 mm long supposedly occurring along crystal cleavage planes. No change was observed in the optical polish near the damage sites. The mechanism for damage appears to be fracture from thermal induced stress and not melting since the thresholds predicted by Eq. (2) for melting exceed the observed values. As might be expected, materials with high absorption coefficients generally had low damage thresholds.

Of the single crystal materials studied, MgF₂ is probably the best volume absorber for CO₂ laser calorimetry. In comparison, the damage threshold of LiF is too low, MgO is expensive and not commonly available, and CaF₂ requires a thick absorber and does not have sufficient absorption near 9.4 μm to cover all potential CO₂ laser wavelengths. CaF₂ would be the best absorber choice for 10.6-μm radiation at very high energy densities.

MgF₂ absorbers were studied in more detail. The damage measurements were extended to include polycrystalline MgF₂ in the form of Irtran 1.[15] Irtran is attractive since the possibility of cracking along cleavage planes is absent. The damage in Irtran 1 occurred between 10–20 J/cm² and did not involve cracking. Small specks on the surface were observed to heat incandescently when exposed to 10–20 J/cm². Under magnification, small pits were seen on the surface; these were probably formed when dirt particles were blown out from beneath the surface. One should avoid blanks with large impurities near the surface. In many instances, however, the numbers and cross sections of impurities are so small as to be negligible. A precleaning of the surface with laser radiation would be feasible to remove imbedded impurities.

MgF₂ in Irtran 1 form was studied for bleaching and effects of cumulative laser pulses. The transmission through a ½-mm thick blank of Irtran 1 exhibited no significant effects of bleaching over an incident energy density range of 0.2–7 J/cm² (0.4–14 MW/cm²). By using a beam splitter to monitor the incident energy, the absorption coefficient could be determined with a precision of 0.5% (one standard deviation at a single value of the incident energy density). With this precision, the absorption coefficient remained constant after exposure to 10,000 laser pulses at an incident pulse energy density of 2 J/cm² (4 MW/cm²). Measurements were also made in an environment with 100% relative humidity at 2% precision (one standard deviation); again, no significant change in the absorption coefficient after 5000 pulses at 3 J/cm² (6 MW/cm²).

To summarize this section, suitable volume absorbers have been found for short pulse laser calorimetry and the limitations of surface absorbers established. Measurements confirm the usefulness of Schott neutral density glass NG-10 at 1.06 μm. At 10.6 μm, single crystal MgF₂ and Irtran 1 were shown to be useful. The damage measurements involved either single or low repetition rate (1-pps or 2-pps) laser pulses. The average power handling capability of the materials in continuous operation was not established. A determination of this capability would involve a knowledge of the material thermal conductivity, thickness, and heat sinking geometry.

III. Calorimeter Design

A calorimeter, referred to as the Q, was designed to utilize solid volume absorbers. Perhaps the most useful feature of the design is calibration against dc electrical standards. Laser energy is determined from the electrical calibration constant without using corrections. This is possible because nearly all the incident laser energy is absorbed in the calorimeter. A rectangular cross-section cavity of 0.2-mm thick electroformed copper holds two volume absorbers (Fig. 1). Two absorbers are necessary if the energy density in the first Fresnel reflection exceeds the damage threshold of black paint. The calorimeter described in this paper is used at 1.06 μm and employs Schott neutral density glasses. For 10.6 μm, MgF₂ or MgO absorbers could be used; only one absorber would be necessary in the case
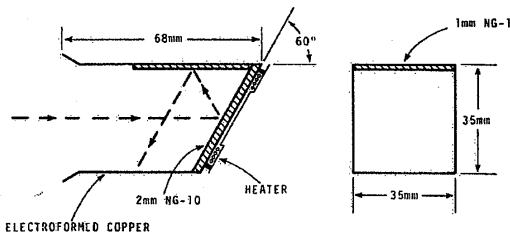
Fig. 1. Side and front cross-sectional views of the Q calorimeter absorbing cavity. Volume absorbers are epoxied inside the 0.2-mm thick electroformed cavity. An electrical calibration heater is epoxied in the groove of a copper spool soldered to the back. The path of a typical light ray is shown.

of MgF₂ because of the low level of Fresnel reflection. In the present Q the main absorber is polished, 2-mm thick NG-10 epoxied to the back of the cavity; previous to gluing both contacting surfaces are sand blasted for good adhesion. The secondary absorber is polished, 1-mm thick NG-1 which absorbs the NG-10 Fresnel reflection. Finally, the NG-1 Fresnel reflection is absorbed by 3M Black Nextel paint.

The laser beam diameters to be encountered determine the aperture of the calorimeter. An aperture of 32 mm × 32 mm enables the calorimeter to accommodate laser beams up to nominally 1-cm diam. Practical experience has shown in most cases a 3:1 aperture to beam diameter ratio reduces overspill and alignment errors.

The calorimeter is electrically calibrated by means of a #36 Manganin wire heater bifilarly wound on a copper spool soldered to the back of the cavity. Copper wire #36 is used to reduce heat generated in the heater leads. Epoxy applied to the spool groove reduces heat lost directly from the heater wire.

The absorbing cavity, supported by four struts of thin wall stainless steel tubing, is enclosed in a constant temperature jacket thus forming an isoperibol calorimeter (Fig. 2). The temperature of the jacket is kept constant by a heater-Wheatstone bridge servo loop chosen to balance about 10 K above room temperature. This method of temperature control has been used on the C and K series, previous NBS laser calorimeters.[16,17] The servo loop stabilizes the temperature of a massive copper ring that is in good thermal contact with the remaining parts of the jacket. The outside of the absorbing cavity as well as the immediate surrounding parts of the jacket are gold plated to obtain stable radiant heat transfer. The front end of the constant temperature jacket is a long baffled tube to reduce the solid angle of the room as seen by the absorber cavity. This baffled tube reduces the effect of room temperature fluctuations and eliminates the need for a window on the calorimeter.

The absorbing cavity is cooled predominately by heat transfer through the 2-cm air gap between cavity and jacket. Heat lost by radiation and conduction through thermopile wires is small. Ignoring epoxy and wire, a heat capacity of 16 J/K is estimated for the absorber cavity shown in Fig. 1; the copper parts of the cavity

account for almost 60% of the heat capacity with the glass responsible for the remainder.

The temperature difference between the absorber cavity and constant temperature surroundings is measured with a 40-junction thermopile. At the entrance, the cavity is slightly flared so the thermopile does not receive direct laser radiation. The hot junctions are spread somewhat uniformly over the sidewalls of the cavity and attached with small drops of epoxy. A uniform distribution of junctions tends to reduce the time required for sensing the average temperature.[11] Cold junctions are epoxied to the constant temperature ring. The voltage from the thermopile is amplified with a dc amplifier, displayed on a digital voltmeter, and recorded permanently on paper tape. A voltage reading is recorded every 4 sec.

Data from the thermopile are analyzed using the assumption of isoperibol calorimetry, i.e., the absorber is assumed to be in surroundings with a constant temperature distribution. A linear model is used to describe the calorimeter. In this model cooling eventually follows a single exponential decay. The Q calorimeter uses the same data analysis and computer program as the C and K series calorimeters described elsewhere.[16,17]

IV. Calorimeter Performance

A. Random Error and Stability

A computer program has been developed to obtain the corrected voltage rise for energy injected to an isoperibol calorimeter.[18] Appropriate parameters were chosen for this curve fit program as described in Refs. 16 and 18. Briefly, part of this program fits by the method of least squares a single exponential to the decaying thermopile voltage before and after energy injection (initial and final rating periods); along with other information, the program gives the corrected voltage rise and cooling constant. Initial and final rating periods of 120 sec (thirty-one data points) were chosen for the present calorimeter. Energy is injected
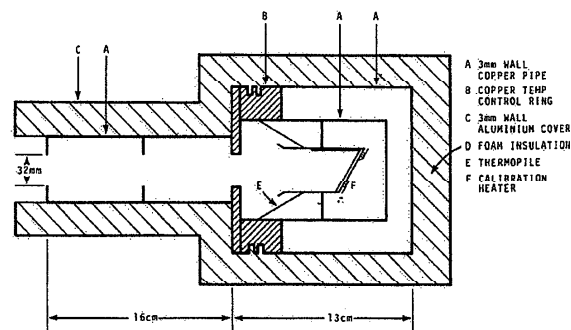

Fig. 2. Cross sectional view of the Q calorimeter showing the absorbing cavity inside the constant temperature surroundings. A stable temperature for the surroundings is achieved by a servo using a Wheatstone bridge and heater epoxied in the grooves of control ring B. The constant temperature jacket is foam insulated from the room environment.
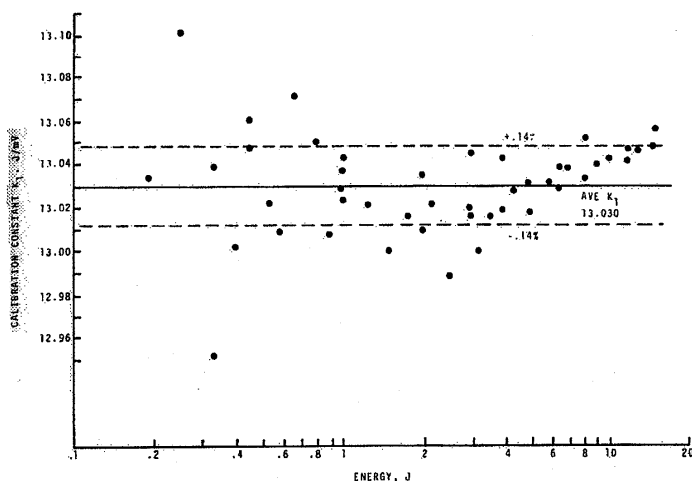
Fig. 3. Calorimeter calibration constant K_1 vs injected electrical energy. K_1 is the injected electrical energy divided by the corrected voltage rise. The operational energy range of the calorimeter is 0.4–15 J. For the forty-two measurements between 0.4 J and 15 J, a mean of 13.030 J/mV is obtained with a standard deviation of 0.14%. One point below the operational range (12.86 J/mV at 0.2 J) was obtained and is not included in the plot. With this single exception, all electrical calibrations made on the calorimeter are indicated in this figure.

to the calorimeter immediately after the initial rating period. The final rating period starts 48 sec after the thermopile voltage reaches a maximum. By this time higher order heat modes have disappeared, and the calorimeter is in a single exponential decay.

In practice, the random error or precision of an instrument is important since an improvement in precision means fewer measurements are necessary to achieve a given level of confidence. Random error is established by making repeated measurements of the calibration constant and noting the standard deviation. The calibration constant K_1 determined by injecting electrical energy into the calorimeter heater is given in Fig. 3 as a function of the energy. The final calibration constant K_3 is determined from K_1 by making a heater lead correction of 0.1%. This correction is necessary since, for convenience, the voltage taps were made at the ends rather than at the midpoints of the heater leads.[16] Figure 3 was used to determine the 0.4-J lower energy limit of the calorimeter. Below 0.4 J the precision becomes unacceptable for our purposes. A standard deviation of less than 0.2% is obtained for the forty-two measurements of K_1 above 0.4 J. A slight trend in the data of Fig. 3 is noticeable especially at the higher energies where the precision is improved. The effects of this nonlinearity will be discussed later under the systematic errors.

The precision and lower energy limit are an indication of the calorimeter temperature stability. A stability of 0.1 mK can be inferred by taking the standard deviation of the eleven measurements of K_1 between 1 J and 2 J and attributing it to temperature fluctuations. A 0.1–0.2-mK fluctuation would be consistent with an observation of the thermopile voltage drift over 360 sec with no energy injected to the calorimeter. Better precision could therefore be achieved by improving the temperature stability.

The constants describing the calorimeter must exhibit good time stability especially after high power

measurements where damage is a possibility. Both calibration and cooling constants are plotted chronologically in Fig. 4 using the forty-two electrical calibrations above 0.4 J (the cooling constant is the reciprocal of the time required for the temperature to decay by a factor of $1/e$). These measurements span a time interval of 6 months. At the time denoted by A, the calorimeter was exposed to several 1-msec pulses from a 1.06-μm Nd-glass laser. There were fifty pulses with
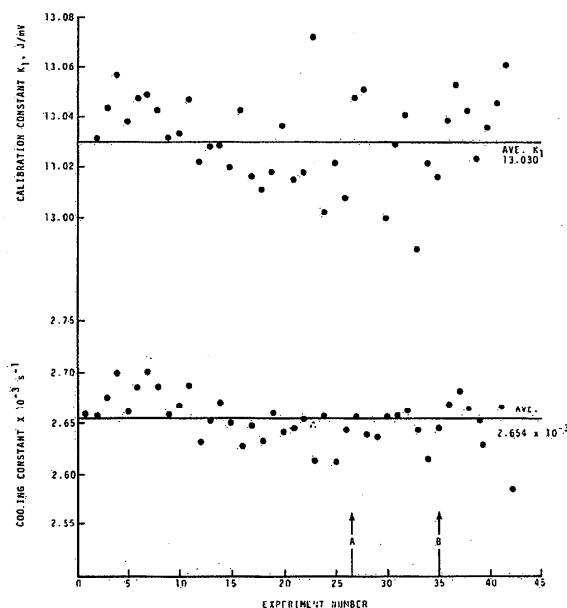

Fig. 4. Calibration constant K_1 and cooling constant for the Q calorimeter plotted chronologically over 6 months. More lower energy measurements were made toward the end of the 6-month period; hence, more scatter occurs at that time. A large number of laser measurements were made at times A and B.

single pulse energies between 2 J and 3 J and energy densities exceeding 2 J/cm²; nine pulses had single pulse energies between 8 J and 12 J with energy densities exceeding 8 J/cm². At a later time B, the calorimeter was exposed to 1000 pulses from a 1.06-μm Q-switched Nd:YAG laser. Individually, these pulses had an energy of 0.2 J, a minimum energy density of 1 J/cm², and a duration of 20 nsec. There appears to be no trend in either the calibration or cooling constant with time. One might expect the cooling constant to decrease with time if the epoxied glass absorbers were to lose contact gradually with the copper cavity. However, this is not the case, and the calorimeter should remain stable unless visible laser damage occurs.

B. Systematic Errors

Systematic error represents the nonrandom offset of the measurement with respect to the true value. In electrically calibrated laser calorimeters, the more significant systematic errors result from an incomplete absorption of the laser energy and an inequivalence between energy supplied by the laser and calibrating heater.

In the Q calorimeter the error resulting from an incomplete absorption of laser energy is negligible; in fact, the reflection from the calorimeter is so low it is difficult to measure. The reflection or backscatter was investigated using a PVF₂ pyroelectric detector. This planar detector had a central 1-mm diam hole and could be placed at the entrance of the absorber cavity.[19] A laser beam passed through the hole, and the backscattered radiation was absorbed on the gold black surface of the pyroelectric. Only cw laser radiation was measured because of chopped, phase sensitive detection. The actual backscatter was too low to be measured; however, a conservative upper limit of 0.1% was established at wavelengths of 0.568 μm, 0.647 μm, and 1.06 μm. For an absorber cavity with no glass but completely painted on the inside with 3M black Nextel paint, a backscatter of 0.2–0.3% was measured at the above wavelengths. By using a Si photodiode radiometer in a dark room, the backscatter of the absorbing cavity with glass could be determined at 0.514 μm with a 0.1-W Ar laser. In this manner, a backscatter of 4 × 10⁻⁴% referred to the input was measured. Also, this technique indicated a backscatter of 0.25% for the black Nextel paint cavity—in agreement with the previous pyroelectric measurements. The backscatter of the glass absorber cavity could be increased by hitting dust particles on the glass surface. A maximum backscatter of 2 × 10⁻³% was observed when the larger dust particles were hit. However, for most of the cavity aperture the backscatter was typically 4 × 10⁻⁴%. The backscatter will exhibit a polarization dependence through the Fresnel reflections, but for our purposes this is negligible.

Inequivalence of sources and smaller systematic errors were determined by intercomparison with an NBS C-series calorimeter. The C calorimeters,[16] used primarily with cw lasers, have systematic errors less than 0.8%. The intercomparison was accomplished using the well known beam splitter technique.[16] Measurements were made using a 0.1-W Kr ion laser at 0.6471 μm with

laser injection times of 40–60 sec. The calibration constant K_2 determined by intercomparison with C4-6 is given in Fig. 5. During these measurements different areas of the calorimeter aperture were illuminated to evaluate errors caused by the spatial distribution of the input; as shown, these errors are insignificant. A discrepancy of 0.05% between the C4-6 and Q calorimeter is indicated with a precision of 0.1% (one standard deviation). The maximum error of a long pulse measurement by the Q calorimeter would be the sum of the following errors: discrepancy between C and Q (0.05%), random error of the intercomparison at the 99% confidence level (0.1%), and error in the C calibration system (1.61%).[20] This means the inequivalence of sources in the Q calorimeter could not possibly be greater than 1.76%. These and other systematic errors are tabulated in Table IV.

An error results from the failure of Q to follow exactly the linear one time constant model of isoperibol calorimetry. As shown in Fig. 3, the calibration constant increases slightly at the higher energies. This effect is believed to be real since it was also observed on a previous calorimeter similar to the presently described Q. A nonlinearity is difficult to imagine since the corrected temperature rise never exceeds 1 K. At present, the effect is unexplained, and a systematic error of 0.15% is taken to cover the maximum increase of K_1 over the average value.

Differences between long electrical and short laser pulses result in systematic errors. For short laser pulses, the surface of the glass is momentarily heated to cause losses by thermal radiation and shock heating of the surrounding air. In volume absorbers the temperature rises occur without phase change and are not extremely large so the results are readily calculable.

Thermal radiation loss is calculated by using Eq. (2) to find the maximum temperature rise. The radiative loss is assumed to be less than the fractional loss, F_1
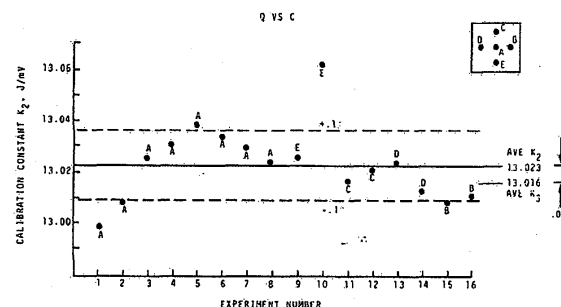

Fig. 5. Comparison of Q calorimeter to NBS C4-6 calorimeter. An average Q calibration constant K_2 of 13.023 J/mV with a standard deviation of 0.1% was obtained for sixteen intercomparisons with C4-6. A discrepancy of 0.05% is indicated between K_2 and the electrically determined Q calibration constant of 13.016 J/mV (K_3). During the intercomparison different areas of the Q calorimeter aperture were illuminated. Measurements denoted by B, C, D, and E were offset from the center (A) by 3 mm. All measurements were made with a 5-mm diam beam. As shown, errors due to beam position are insignificant.

Table IV. Systematic Errors of the Q Calorimeter

Source of error	Maximum absolute value
(1) Incomplete absorption of laser radiation—determined by measurement	Negligible
(2) Inequivalence of sources and errors relating electrical energy to the SI units—determined by intercomparison with C calorimeter	
(a) Discrepancy between C and Q	0.05%
(b) Random error of intercomparison at 99% confidence level	0.08%
(c) Systematic error of C series calibration system	1.61%
(3) Failure of calorimeter model—determined by measurement	0.15%
(4) Inequivalence between long electrical and short laser pulses—determined by calculation	
(a) Thermal radiation (0.02%)	Included in C intercomparison
(b) Shock heating of air	0.4%
Total systematic error	±2.3%

occurred by having the surface at maximum temperature $\Delta T(0)$ for three time constants τ. As will be discussed later, the calorimeter is operationally limited to 3 J/cm² giving a maximum rise $\Delta T(0)$ of 38 K. For this rise, the radiative heat transfer can be linearized, and F_1 is given by

$$F_1 = \left(\frac{6\xi\sigma T_s^3}{\alpha K}\right) f, \qquad (4)$$

where ξ is the emissivity (assumed to be one), σ the Stefan-Boltzmann constant, T_s the temperature of the surroundings, and f the solid angle of the cavity entrance compared to 2π sr. For NG-10 at 1.06 μm, the term in parenthesis in Eq. (4) is 0.3% and when multiplied by f gives an F_1 of 0.02%. At energy densities where linearized Eq. (4) is valid, the thermal loss should be independent of pulse duration and is therefore included in the intercomparison with C4–6. If higher energy densities are used, the fourth power dependence in the radiative loss becomes important, and Eq. (4) is no longer valid. Using no linearization, F_1 becomes 0.3% at a 55-J/cm² damage limit.

Energy is also lost by heating quickly the air immediately in front of the absorbing surface. This is most evident in some cone calorimeters that produce a loud noise upon absorbing a Q-switched laser pulse, in the Q calorimeter no audible noise is produced. The loss due to fast air heating is assumed to be less than the fractional energy F_2 required to heat to $\Delta T(0)$ a volume of air extending a distance $[(2K'\tau)/\rho'c')]^{1/2}$ in front of the glass surface. F_2 is given by

$$F_2 = \left(\frac{K'\rho'c'}{K\rho c}\right)^{1/2},$$

where the prime superscripts refer to air and the un-

primed to glass. F_2 has a value of 0.4% and is included in Table IV.

C. Operational Limits

The operational limits of the Q calorimeter with Schott NG-10 absorbing glass are summarized in Table V. A value of 3 J/cm² has been chosen for the upper energy density limit. This provides more than an order of magnitude safety factor with respect to damage. Such a safety factor is desirable since lasers often have nonuniform beams, and it is difficult to determine the maximum energy density. Moreover, the damage measurements were made with relatively small diameter beams. The maximum pulse repetition rate was chosen as 10/E, where E is the maximum energy density per pulse in J/cm². At this rate there are three time constants τ between pulses at the maximum energy density of 3 J/cm². During this time, the surface temperature should decay so the next pulse can be safely absorbed. An absorber cavity was tested by using a 0.2-J/pulse repetitively Q-switched Nd:YAG laser at a pulse energy density of 1 J/cm². No damage was observed after exposing the cavity at 10 pps for 300 sec. Also, the same cavity was not damaged by a 300-sec exposure to a 2-W cw Nd:YAG laser at 7 W/cm².

The lower energy range of Q, 0.4 J, is determined by a loss of precision while the upper limit, 15 J, is determined by nonlinearities.

The peak power limitations of the calorimeter will be determined by a peak power damage mechanism in NG-10 glass. The minimum pulse length used in this study was 20 nsec; however, measurements by Gunn indicate absorbing glasses can be used down to 0.2 nsec without decreasing the energy density damage threshold.

Only a single wavelength, 1.06 μm, was used to determine the high power properties of NG-10. However, it is likely the glass can be used from 1.2 μm down to at least 0.5 μm. At wavelengths longer than 1.2 μm, the absorption coefficient starts to decrease significantly. At wavelengths shorter than 0.45 μm, the absorption starts to increase significantly.

V. Conclusion and Discussion

There has been a need for a standard, reference cal-

Table V. Specifications of the Q Calorimeter with NG-10 Main Absorber

Aperture size	32 mm × 32 mm
Cooling constant	0.00265 sec⁻¹
Maximum energy injection time	40 sec
Random error (one standard deviation)	0.2%
Systematic error	2.3%
Energy range	0.4–15 J
Maximum energy density per pulse	3 J/cm²
Maximum pulse repetition rate, where E is the energy density per pulse in J/cm²	10/E pps
Minimum pulse width	20 nsec documented 0.2 nsec probable
Wavelength range	1.06 μm documented 1.2–0.5 μm probable

orimeter to measure the energy in high power laser pulses. A Q calorimeter utilizing solid volume absorbers was developed to meet this need. The precision and accuracy were determined for an instrument using Schott neutral density glasses. The precision is 0.2%, and the systematic error is less than 2.3%. To extend the wavelength range, other volume absorbers can be used in the calorimeter. Single and poly crystals such as MgF_2 would improve the thermal performance of the calorimeter. A higher thermal diffusivity in the absorber means less time is required to achieve thermal equilibrium.

The design of the Q calorimeter contains a number of desirable features. These features enable measurements to be made simply with less maintenance of the calorimeter. No corrections are necessary for a window or for absorptance of the calorimeter.

A spin-off of the current work is a realization of the low backscatter achieved by polished glass absorbing cavities. Reflections from polished glass surfaces are almost totally specular with a very low diffuse component. It is therefore possible to calculate simply by ray tracing the amount of radiation escaping the cavity. By using thin glass bonded to a thin copper substrate, one can design high absorptance, specularly flat cavities of low heat capacity and high thermal diffusivity.

As discussed previously, the systematic error of the Q is at 2.3%. A significant amount of the error (1.8%) comes from evaluating the inequivalence of sources by intercomparison with the C calorimeter. The actual discrepancy between Q and C is small; however, a rather large error results when all the random and systematic errors of the calibration system are accumulated. A more direct way to establish the inequivalence would be to inject electrically energy on the front surface of the glass absorber by means of a deposited thin film resistor and compare this response to the back wire heater used for electrical calibration. In the opinion of the authors, the inequivalence error is substantially less than 1.8%.

In this paper a rather brief description was given of the Q calorimeter construction. A more complete description, including machine drawings, will be published in the future as an NBS Technical Note.

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